

A Suggested Approach for Developing
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**A SUGGESTED APPROACH FOR DEVELOPING
ESTUARINE WATER QUALITY CRITERIA
FOR MANAGEMENT OF EUTROPHICATION**

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ABSTRACT: A conceptual approach for developing water quality criteria for eutrophication management is suggested. The three basic components of the framework include source ambient relationships, effects, and impact analyses. The approach focuses on a conceptual method for developing decision-making criteria as opposed to the classical water quality criteria of a single value of limitation. The approach to developing water quality criteria for eutrophication management provides an analysis framework of response relationships which can be readily incorporated into water quality standard-setting processes that include environmental considerations and technological and economic factors.

INTRODUCTION

The objective of the U.S. Federal Water Pollution Control Act, as amended, is to "Restore and maintain the chemical, physical, and biological integrity of the Nation's waters." An integral part of the Act is the promulgation of water quality standards and the issuing of water quality criteria accurately reflecting the latest scientific knowledge on the kind and extent of all identifiable effects on health and welfare which may be expected from the presence of pollutants in any water body.

The three major scientific considerations in developing water quality criteria for a pollutant in a given water body and water use are:

1. An analysis of the sources, concentration, dispersal, transformation, and availability through physical, biological, and chemical processes;

2. The kind and extent of all identifiable effects on the health and welfare of humans and their environment;
3. The impact of these effects on humans and on the diversity, productivity, stability, and utility of the biological community.

The above three considerations are generally applicable to the developing of water quality criteria for any pollutant.

APPLICATION TO EUTROPHICATION

Since the 1960s, considerable research effort has been conducted to aid in developing sound approaches to the control of eutrophication in fresh water systems, with considerably less effort on estuarine systems. With prudent use much of the information and analysis techniques developed for fresh water systems can be applied to estuarine systems.

The overall goal of eutrophication control can be generally stated as "to maintain a balance between the various nutrients and a balance of the biota conducive to the production and/or protection of a healthy ecosystem." Some general indicators of excessive eutrophication in marine systems and fresh water systems are:

1. An increase in the dissolved oxygen deficit in the hypolimnion in lakes, or in the lower water column depths in estuaries;
2. An increase in dissolved solids (not for marine systems), especially nutrients, such as nitrogen and phosphorus;
3. An increase in suspended material, especially organic;
4. A shift from diatom-dominated plankton populations to those dominated by blue-green or green algae;
5. A decrease in light penetration;
6. An increase in the concentration of organic compounds and nutrients in the benthic deposits;
7. A potential production of toxins mainly from massive blue-green algal blooms in fresh water systems and from "red tides" in marine systems;
8. An increase in biomass and primary production;
9. The presence of nuisance seasonal algal blooms.

In the management of eutrophication, the development of specific water quality criteria is much more difficult to formulate than the management of most toxic pollutants. This difficulty arises in that overenrichment may have both beneficial and detrimental impacts on an ecosystem. In addition, no definitive indicators have been developed which can be used as specific "end points" to assess a given criteria. Some indicators often used in eutrophication management are the maintenance of a given chlorophyll concentration, productivity level, or transparency

level. In developing specific requirements of eutrophication management for fresh water systems, limits on phosphorus and nitrogen are often suggested.

Many approaches in developing nutrient criteria in fresh water are applicable to estuarine systems. However, there are considerable differences between fresh water and estuarine systems including nutrient cycling, transport and transformation, physical hydrodynamics, indigenous species, and degree of salinity intrusion.

Although considerable research has been conducted in determining how to remove nutrients from wastewater discharges and how to better understand the ecosystem, little effort has gone into determining to what degree the ecosystem should be managed—that is, to quantify water quality criteria for eutrophication control, including control cost and ecosystem response and benefits. This paper discusses an approach to aid in quantifying water quality criteria for eutrophication management requirements. The approach focuses on a conceptual method for developing decision-making criteria as opposed to the classical water quality criteria of single value limitation.

VARIOUS APPROACHES TO DEVELOPING WATER QUALITY MANAGEMENT CRITERIA

Review and Extension of Historical Data

Various investigators studying nuisance conditions in fresh and estuarine water systems have suggested criteria for nitrogen and phosphorus needed to control algal blooms. In a study of the Occoquan Reservoir on a tributary of the Potomac, Sawyer (21) recommends limits of inorganic nitrogen and inorganic phosphorus of 0.35 and 0.02 mg/l, respectively. Mackenthun (13) cites data indicating the upper limits of inorganic nitrogen at 0.3 mg/l and inorganic phosphorus at 0.01 mg/l at the start of the growing season to prevent algal blooms. Pritchard (17), studying the Chesapeake Bay and its tributaries, suggests that if the total phosphorus concentration in estuaries is less than 0.03 mg/l, biologically "healthy" conditions will be maintained. Jaworski, et al. (10), reviewing the historical data for the upper Potomac estuary, suggests that if concentrations of inorganic phosphorus ranging from 0.03 to 0.1 mg/l and inorganic nitrogen from 0.3 to 0.5 mg/l were maintained in the upper estuary, a chlorophyll level of about 25 µg/l could be maintained under normal conditions during the summer growing season. There are no current federal water quality criteria for estuarine waters (18).

Use of Indices

Another approach to developing water quality management criteria is the integration of numerous water quality and ecosystem parameters into an index. The use of indices to set eutrophication control requirements for studies has been mainly limited to fresh water ecosystems (19). Included in the relationships are nitrogen and phosphorus concentration, transparency, turbidity, chlorophyll, dissolved oxygen, and productivity. Frank F. Hooper (8) suggests several criteria for a good index. It should differentiate between changes in enrichment levels and seasonal and climatic cycles. It should be sensitive to enrichment levels and indicate the presence or absence of organisms over a period of time to reduce the extent of monitoring. It should indicate values that are widespread geographically and sensitive to cultural changes, and it should be practical to use in terms of simplicity, interpretation, and collection of data. McErlean (12) expands further on this concept for marine systems.

Use of Ecosystem Mathematical Models

In both freshwater and marine systems, mathematical models of ecosystems have been used to help delineate eutrophication control management requirements. Approaches ranging from simple to very complicated models have been applied to the Potomac estuary (10), Chesapeake Bay (20), and Narragansett Bay (14) in marine systems and to fresh water systems such as the Great Lakes (5). Further elaboration of ecosystem estuarine modeling is presented by O'Connor (15).

Subjective Analysis

To aid in developing water quality criteria in freshwater systems, three terms have been suggested: oligotrophic, mesotrophic, and eutrophic. These subjective terms were used by Vollenweider (23) in suggesting total phosphorus loading in grams per square meter of surface area per year that would be "permissible" or "excessive" for a lake ecosystem. Included in the approach were physical parameters such as mean depth of the lake and hydraulic residence time. This approach was applied to the Potomac estuary by Jaworski (9) as part of the North American project of OECD. The effort was further extended by Lee and Jones (11).

Use of Benefit/Cost Analysis

One of the first attempts at using this method, employing both cost of nutrient control and benefit of nutrient control in developing water quality criteria, was for the San Joaquin drainage basin by Bain, et al., in 1968 (1). In this approach, rather than trying to set a nutrient level based solely on historical data, the use of indices, or subjective analyses, an

attempt was made to relate the nutrient level in the system to a given biomass and then relate the biomass to a dollar value of benefits.

Analysis of Various Approaches

In each of the above approaches, except for the benefit/cost analysis, a "single value" parameter usually evolves; e.g., a suggested maximum concentration level for phosphorus or nitrogen. As suggested in a recent report by the Council on Wage and Price Stability (4), water quality criteria should reflect "estimates of the effects on human and aquatic life of different concentrations of various substances instead of setting maximum suggested concentration levels." The different levels (dose-response) can be more rapidly utilized in developing water quality standards which involve determining the use attainable for specific bodies when environmental, technological, and economic factors are taken into consideration. While all of the above approaches can aid in developing water quality criteria for estuarine systems, they all are somewhat lacking (in the opinion of the authors) in addressing the three major scientific considerations presented earlier in this paper.

The establishment of the U.S. Regulatory Council also reflects the current concern in this country to more rigorously determine environmental benefits from environmental control systems. Therefore, it is now more prudent than ever to emphasize the third component of developing water quality criteria: the impact on the ecosystem. The next sections present a suggested procedure for developing water quality for eutrophication management for estuarine systems.

BASIC CONSIDERATIONS FOR DEVELOPING WATER QUALITY CRITERIA FOR EUTROPHICATION MANAGEMENT

Although the approach presented in this paper is mainly conceptual, the various relationships suggested are those often utilized in ecosystem studies. This approach links the key relationships into a hierarchical framework allowing for successive decision making.

Listed below are some of the basic considerations that were used in developing the approach:

1. Inclusion of key physical/chemical/biological processes of estuarine systems;
2. Relationships to key existing water quality parameters (e.g., dissolved oxygen);
3. Provision of trade-off options for management consideration;
4. Indication of the sensitivity of the various relationships;
5. Translation into simple and inexpensive monitoring parameters upon implementation;

6. Readily presentable to and understandable by decision makers.

Considerable effort has been made to keep the framework relatively simple. If future studies indicate that other relationships are needed, they may be added to the conceptual framework.

The proposed framework includes the following basic elements:

1. Physical attributes of the estuary;
2. Designated water uses of the estuary;
3. Nutrient source/ambient relationship;
4. Nutrient/aquatic biomass relationship;
5. Biomass/oxygen resource relationship;
6. Biomass/estuarine productivity relationship;
7. Biomass/aesthetics relationship.

In the approach that follows, the three general scientific considerations required in developing water quality are linked in a framework through the above elements.

SUGGESTED FRAMEWORK FOR DEVELOPING WATER QUALITY CRITERIA

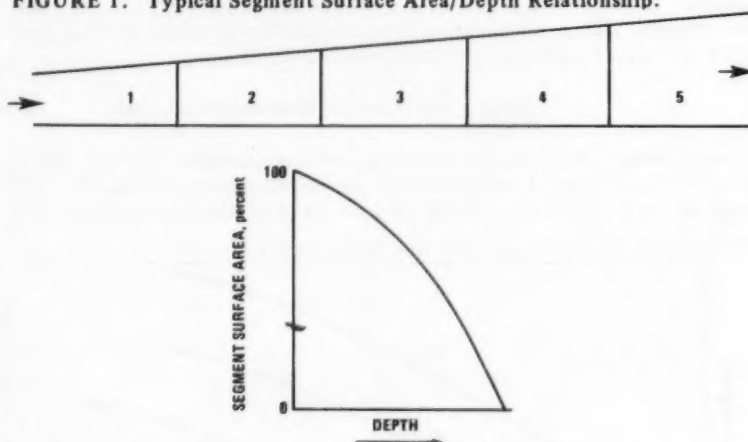
Segmentation of the Estuarine System

The first step in this approach to developing water quality criteria is to segment the estuary according to its physical, chemical, and biological properties including designated water uses. For example, Lake Erie was divided into three segments based on depth as part of the International Joint Committee eutrophication study. Factors which should be taken into consideration are the hydrodynamics, salinity, and the various uses of the water such as recreation, oystering, and fishing. A segment surface area/depth relationship should be developed as shown in Figure 1. This relationship has utility in the analysis of oxygen resources and in the delineation of those areas which have important aquatic considerations, including commercial and recreational potential. For example, those segments which mainly attract recreational use can be examined critically for aesthetic aspects.

Nutrient Source/Ambient Relationship

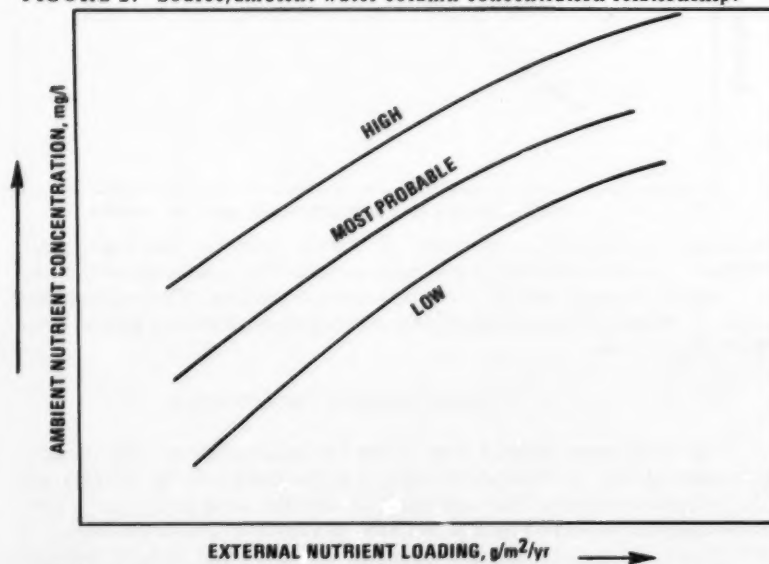
For a given nutrient and segment, the development of a source/ambient water column concentration relationship (as shown in Figure 2) indicates the chemical, biological, and physical response of an ecosystem to external sources. Such responses can be developed by examining existing data and by using simple to very complex models. Because of uncertainty,

FIGURE 1. Typical Segment Surface Area/Depth Relationship.



high, most probable, and low estimates should be developed. These types of relationships have been developed for the Great Lakes (22).

FIGURE 2. Source/ambient water column concentration relationship.



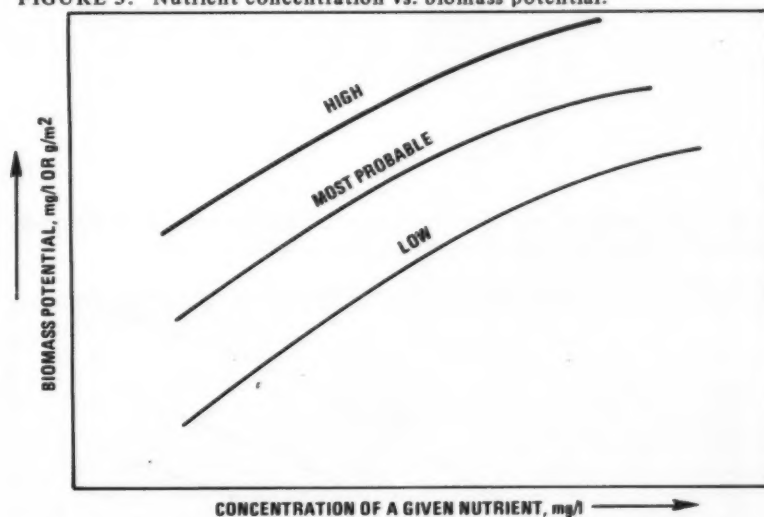
This relationship can be for annual loading in grams per square meter of surface area per year or on a more short term basis such as seasonally or

monthly. If atmospheric or benthic sources are important, they can also be included. These relationships have an additional utility in that they allow an easy comparison between similar water bodies.

Estimate of Nutrient/Biomass Relationship

After having developed the source/ambient relationship, the next step is to develop a nutrient concentration versus biomass potential for each segment in a given time frame (Figure 3). For this relationship, it is

FIGURE 3. Nutrient concentration vs. biomass potential.



necessary to develop a sequence of curves including the high, most probable, and low estimates for various seasons. This relationship could be for rooted aquatic and/or for planktonic organisms. The relationship could be developed either from laboratory chemostat studies and/or from field observations.

Oxygen Resources Considerations

As in fresh water systems, one of the key parameters in water quality management for eutrophication control is the impact of the biomass on the oxygen resources. This approach divides the oxygen resources into three systems: 1) net oxygen production as a result of photosynthesis and respiration, 2) benthic oxygen demand, and 3) water column oxygen demand. Treating the three systems separately is facilitated by incorporating the surface area/depth relationship shown in Figure 1.

FIGURE 4. General net oxygen production/depth relationship.

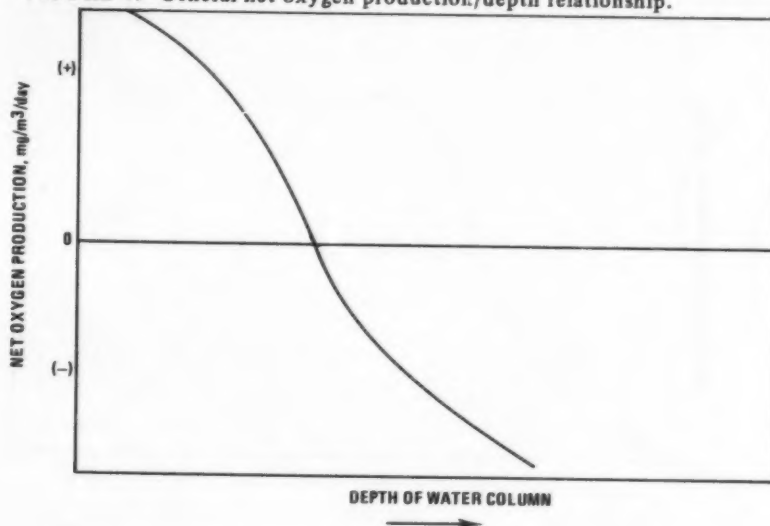


Figure 4 presents a general net oxygen production/depth relationship due to either planktonic or rooted aquatic growth. Examples of this were used in the San Joaquin study (1) and in the Potomac estuary studies (3).

The second component of the oxygen resources considerations is a general benthic oxygen demand/time relationship for given biomass concentrations as shown in Figure 5. Studies of the Narragansett Bay (16), suggest that relationship as shown in Figure 5 can be developed for each segment of the estuary. Additional verification of this can be developed from benthic respirometer studies such as those conducted in the Potomac estuary (10) and Narragansett Bay (16).

The third component is the estimate of water column oxygen demand attributed to the eutrophication process. Analyses of data in field studies of the Potomac estuary (3), Narragansett Bay (16), Albemarle Sound (2) and New York Bight (7) have shown that a large percentage of inorganic carbon is converted to the organic form during eutrophication. Eutrophication not only significantly increases the amount of organic carbon in these estuarine ecosystems, but also can significantly add to the water column dissolved oxygen demand. Relationships, as shown in Figure 6, can be developed for each segment of the estuarine system.

By using the theory of superposition, a general total oxygen deficit/biomass relationship for a given season can be evolved as shown in Figure 7. This total relationship includes the photosynthesis/respiration, water column oxygen demand, and benthic oxygen demand terms. It may also be possible to develop this relationship directly as suggested by the efforts developed by Dobson (6) for Lake Erie.

FIGURE 5. General benthic oxygen demand/time relationship.

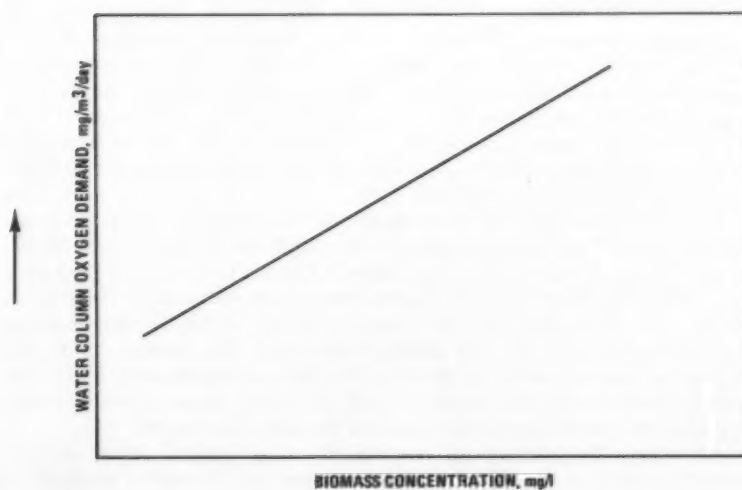
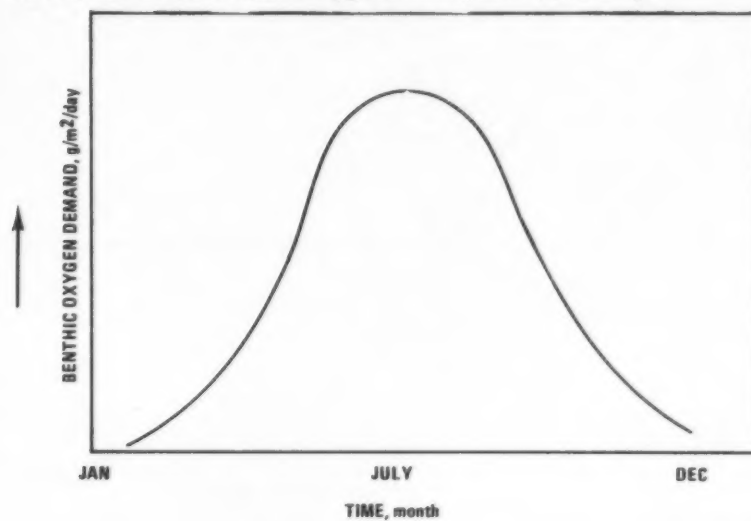
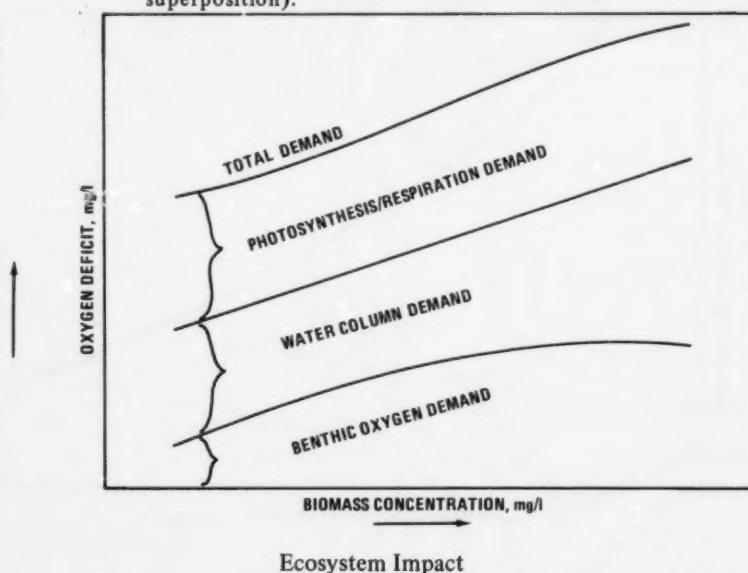


FIGURE 6. Water column/dissolved oxygen demand relationship.

FIGURE 7. General total oxygen deficit vs. biomass relationship (by superposition).



This approach incorporates three ecosystem impact considerations. Figure 8 shows a general relationship between biomass concentration, dissolved oxygen concentration, and surface area. The dissolved oxygen concentration/biomass relationship is a further incorporation of the surface area/depth relationship shown in Figure 1, and the relationships developed in Figures 4-7. These relationships permit quantification on an area basis of the impact of biomass on the dissolved oxygen resources of the segment. Further expansion of this concept is required to fully implement this impact.

A second impact, indicated in Figure 9, is the transparency/biomass component, a major aesthetic and ecosystem stress consideration when considering such activities as boating and swimming. Further expansion of this impact could include the water transparency versus nutrient relationship developed by Lee and Jones (11).

A major indicator of the eutrophication process is the increase in the biomass of the ecosystem and its biological value. This increase can have a beneficial or detrimental impact on the ecosystem food chain depending on the "desirability" of the increase in the food chain. If the ecosystem is at a desired balance, it can be argued that there will be a minimal buildup in unusable cellular material. It can further be argued that if the cellular material increase is not readily assimilated in the food chain, the increase

FIGURE 8. General biomass concentration vs. dissolved oxygen concentration vs. surface area concentration.

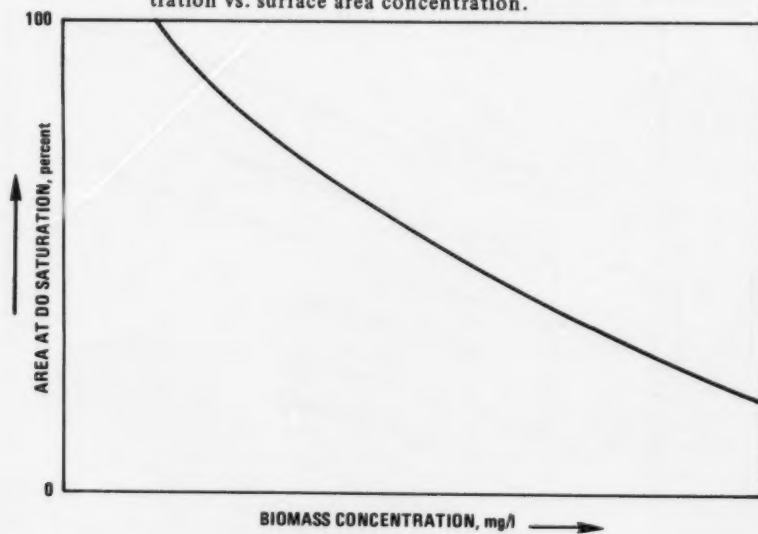
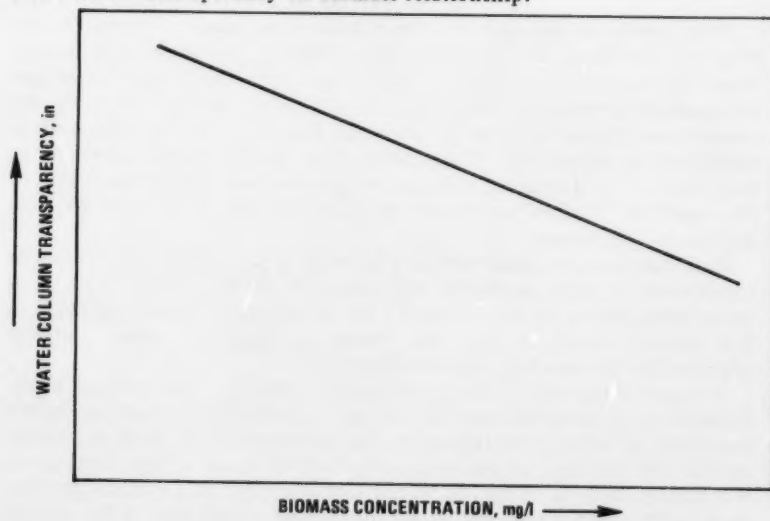
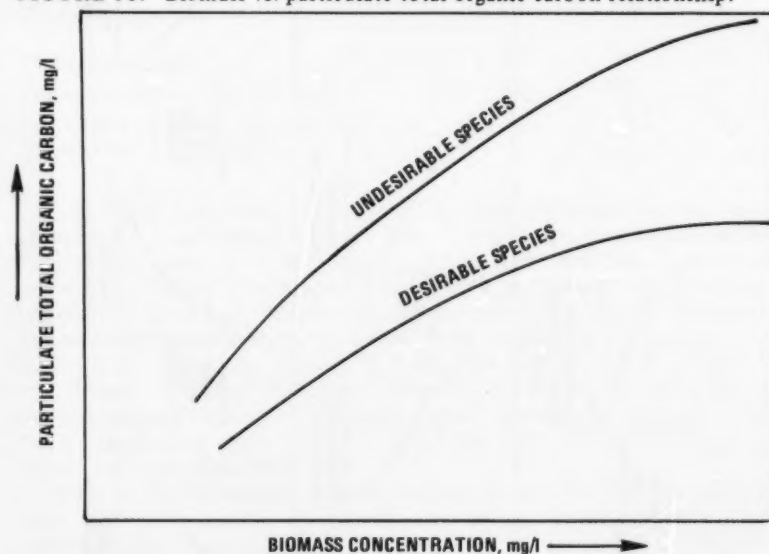


FIGURE 9. Transparency vs. biomass relationship.



will be particulate cellular material, as indicated in the particulate total organic carbon measurement. Figure 10 suggests a relationship between

FIGURE 10. Biomass vs. particulate total organic carbon relationship.



biomass and particulate total organic carbon. Further expansion of this concept is required to fully implement the incorporation of this impact.

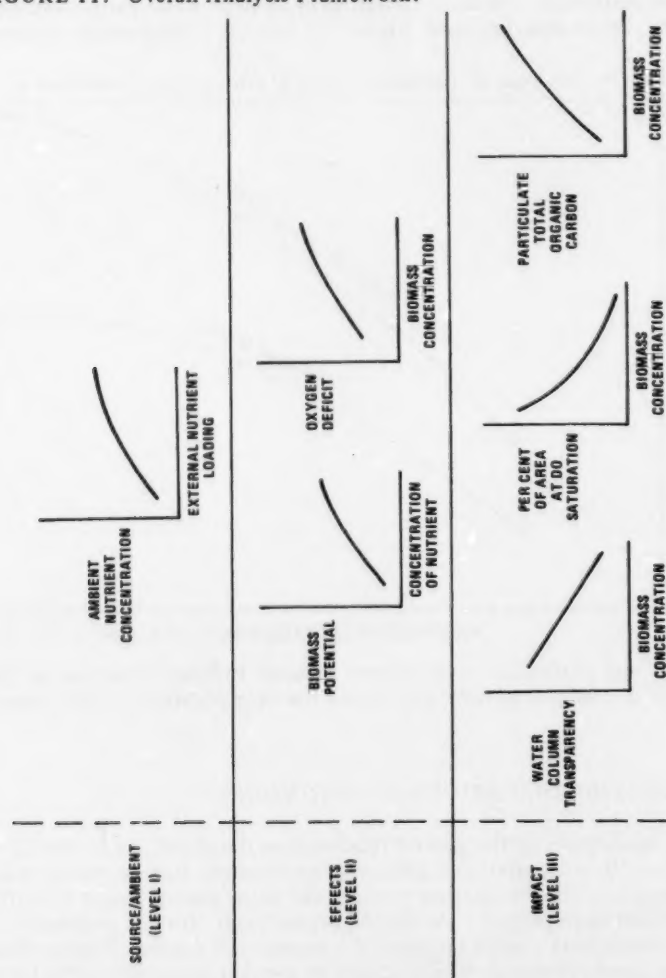
INTEGRATION OF VARIOUS RELATIONSHIPS

The integration of the general relationships developed, as presented in Figures 2-10, is incorporated into an overall analysis framework as shown in Figure 11. This integration includes the three general major scientific considerations employed in developing water quality for any pollutant.

The framework can be considered a hierarchical analysis flowing from Level I (source/ambient relationships) to Level II (ecosystem effects) to Level III (ecosystem impacts). In this hierarchical concept, the complexity and interdependence increase as the level of analysis increases. However, it allows decisions to be made at each level, depending on the degree of analysis required.

To illustrate the utility of the approach, three hypothetical cases are presented in Tables I-III which could represent typical conditions in east coast estuaries. Hypothetical Case I represents the response of three

FIGURE 11. Overall Analysis Framework.



phosphorus loadings on the three ecosystem impact considerations. In this case, a desired aquatic community is assumed. Case II is similar to Case I except the aquatic community is assumed to be "undesirable." Case III is the same as Case I except the average depth is 15.0 m instead of 5.0 m. (A further assumption is that the nutrient and biomass concentrations are the same).

TABLE 1. Hypothetical Case I. - (Average Depth = 5.0 m) (Major Use: Recreation and Commercial Fishing)

Ecosystem Impact	Phosphorus Loading, g/m ² /yr		
	1.0	2.0	5.0
Transparency, in.	40	30	10
Percent of Area at DO Saturation	90	90	90
Particulate Organic (mg/l) Carbon ("desirable" community)	2	3	5

Cases I and II represent the trade-off between recreation and desirable productivity (commercial fishing). Case I would favor recreation while Case II does not. Case II would probably not have any impact on commercial fishing. The trade-off is between an increase in particulate organic carbon and the decrease in transparency. Cases I and III represent the trade-off between desirable productivity and oxygen resources. The trade-off is between an increase in food chain organic carbon in Cases I and III and a decrease in oxygen resources in Case III. The decrease in oxygen resources could significantly impact commercial fishing. These three hypothetical cases vividly represent the need to include ecosystem impact in the decision framework.

This analysis framework (Figure 11) overcomes one of the historically most difficult aspects of developing water quality criteria for eutrophication management - the inability to develop well defined parameters indicative of the impact of overenrichment. Instead of the maximum concentration concept, this approach provides an analysis framework of response relationships which can be readily incorporated into the water quality standard-setting process to include not only environmental considerations but also technological and economic factors.

TABLE 2. Hypothetical Case II. - (Average Depth = 5.0 m) (Major Use: Recreation and Commercial Fishing)

Ecosystem Impact	Phosphorus Loading, g/m ² /yr		
	1.0	2.0	5.0
Transparency, in.	50	40	30
Percent of Area at DO Saturation	90	90	90
Particulate Organic (mg/l) Carbon ("undesirable" community)	5	7	12

While the approach does not yield specific values for "excessive" or "permissible" concentrations for eutrophication parameters, it does provide a framework for analysis on a multi-level response basis. It also

TABLE 3. Hypothetical Case III. - (Average Depth 15.0 m) (Major Use: Recreation and Commercial Fishing)

Ecosystem Impact	Phosphorus Loading, g/m ² /yr		
	1.0	2.0	5.0
Transparency, in.	40	30	10
Percent of Area at DO Saturation	80	60	30
Particulate Organic (mg/l) Carbon	2	3	5

provides for a trade-off between the various impacts of overenrichment which may be both beneficial and detrimental to a given ecosystem.

SUMMARY

A conceptual approach for developing water quality criteria for eutrophication management is suggested. This approach incorporates:

1. A multi-level hierarchical framework for developing water quality criteria for eutrophication management on a multi-response basis.
2. Key nutrient source/ambient, ecosystem effects, and ecosystem impact relationships.
3. Linkages which can be used in a simplified form or expanded into ecosystem models.
4. Uncertainties of the various relationships.

To aid in further development of water quality criteria for eutrophication management on a scientific basis, the following are suggested:

1. Greater development of ecosystem impact relationships due to overenrichment. Three possible relationships presented in this approach require further development and field testing.
2. Greater development and application of simple and inexpensive monitoring parameters, including such possible measurements as various nutrient forms, chlorophyll, and various forms of total organic carbon to aid in ecosystem impact analysis.

The approach has reduced many complex ecosystem relationships into simple forms. The intent is to put development of water quality criteria aspects in a usable form for decision-makers. It is also intended to provide an opportunity for the biologist, chemist, engineer, and hydrodynamist to understand the linkages between the various scientific fields required in developing water quality criteria for eutrophication management.

It is not the intent of this approach to minimize the complexities of the physical, chemical and biological processes of eutrophication; rather the intent is to establish a simplified and orderly approach so that future research can be organized into a framework that is logical, uncomplex, and understandable. The goal of this approach is to aid in developing a scientific basis for the developing of water quality criteria for the management of overenrichment of estuarine systems.

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